

Solar micro-energy harvesting based on thermoelectric and latent heat effects. Part I: Theoretical analysis

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ABSTRACT

This article presents a new method of harvesting ambient renewable micro-energy by using both thermoelectric and latent heat effects. We designed a prototype work unit made of phase change material (PCM) and a thermoelectric generator (TEG) and used a numerical method to inspect system performance. Special attention was paid to the implementation of ambient loading (including solar radiation, temperature variation and wind speed) in the numerical simulation process. The calculated results show that the proposed work unit (TEG & PCM) can harvest micro-energy day and night, thanks to the heat storage function of the PCM which is placed behind the TEG.

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1. Introduction

Current solutions for reducing dependence on fossil energy in buildings involve such power needs as those of heating, cooling and lighting. The increasing development of photovoltaic panels, solar thermal, geothermal and other similar solutions reflects the interest in harvesting renewable energy for high-power applications in dwellings.

In a building there are many devices which consume low-power energy; most are powered by batteries and some are used to control electrical switches for energy-saving systems or comfort systems in the building. For these low-power devices, there are no studies on the harvesting of renewable micro-energy. The aim of this article is to present a means of harvesting renewable micro-energy which uses both thermoelectric and latent heat effects. Ultimately, the proposed solution would involve sensors and actuators operating wirelessly on electrical switches connected to the thermal or comfort systems of buildings.

In a continuation of our work on vibration-damping [1] and micro-energy harvesting [2,3] based on the piezoelectric effect [4], we study here micro-energy harvesting with the coupling of the thermoelectric and latent heat effects. It is the combination of these two effects, which have been widely, but separately

studied in the literature, that is the central innovation of this study.

Several separate studies have been made on (i) thermogenerators (Thermo Electric Generator – TEG) and (ii) phase change materials (PCMs) used in buildings.

Regarding the TEG, the main results show that it can be used to generate electricity [5–7], to measure temperature and to heat or cool objects [8,9]. Thermogenerators can be applied in a variety of situations. Usually, they are used for small applications where larger (and more efficient) thermoelectric conversion systems (e.g. the Stirling engine) are not possible. The use of waste heat in combustion engines promises to be a high-volume field of application [10]. TEG power generation is based on the heat flux through a thermoelectric element comprising many such elements. The heat flux is driven by temperature difference across the element (variation of the temperature as a function of the space variable) and the thermogenerators produce voltages depending on actual temperature differences. The basic thermoelectric effect of the TEG is therefore the direct conversion of temperature differences to electrical voltage and vice versa (known as the Peltier–Seebeck effect). A thermoelectric device creates a voltage when there is a different temperature on each side of it. Conversely, when a voltage is applied to it, it creates a temperature difference (Peltier effect). At the atomic scale (specifically, charge carriers), an applied temperature gradient results in charged carriers in the material, either electrons or holes, to diffuse from the hot side to the cold side, like a classical gas that expands when heated: hence the thermally induced cur-

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rent. Because the direction of heating and cooling is determined by the sign of the applied voltage, thermoelectric devices make very convenient temperature controllers. The review shows that a low thermal conductivity is required for a good TEG. For example, it is not simple to place a TEG on an essential IC chip that requires cooling. Because of the low thermal conductivity of a TEG device, the IC is cooled at a slower rate.

Most work on TEGs shows typical efficiencies of around 5–10% [5,11]. Thermoelectric modules are the main device used for harvesting energy from temperature. It is now possible to find commercial thermoelectric generators with from μW to kW in electrical output. They are based on temperature gradients leading to heat flow through the thermoelectric generator; a small percentage of the heat flow is converted to electrical energy. Material properties are the key parameter for improving both output power (increase of thermal heat flow) and efficiency (improvement of Seebeck coefficient). The main problem with the use of TEGs for converting ambient energy into electrical energy is that of maintaining a high temperature gradient (variation of temperature with space variable) when the loading is time-variable, as it is in solar heating. The harvested energy is directly proportional to the temperature gradient. The proportionality coefficient depends on the kind of TEG used.

Over the last 20 years, there has been a considerable variety of literature on PCM. Zalba et al. [12] reviewed the history of thermal energy storage with a solid–liquid phase change, focusing on three aspects: materials, heat transfer and application. The main results on PCM show that it has many possible applications, such as (i) thermal energy storage [13,14], (ii) the air-conditioning in buildings [15–17], e.g. the “ice-storage” cooling of heat and electrical engines, (iii) the cooling of food, wine, dairy products, green-houses, (iv) medical applications: transportation of blood, operating tables, hot-cold therapies, (v) waste heat recovery [18,19], (vi) off-peak power: heating water and cooling, heat pump systems, and (vii) passive storage in bioclimatic building/architecture (HDPE, paraffin), thermal comfort in vehicles, textiles used in clothing and computer cooling.

The characteristics of phase change material (PCM) are similar to those of substances which melt and solidify at a high fusion temperature. The material can store and release large amounts of energy. Heat is absorbed or released when the material alternates between solid and liquid; PCMs are thus classified as latent heat storage (LHS) units. PCM latent heat storage is generally achieved through a solid–liquid phase change. Initially, the solid–liquid PCMs behave as sensible heat storage (SHS) materials: their temperature rises as they absorb heat. Unlike conventional SHS, however, when PCMs reach the temperature at which they change phase (their melting temperature) they absorb large amounts of heat at an almost constant temperature. The PCM continues to absorb heat with no significant rise in temperature until all the material has become liquid. When the ambient temperature around a liquid material falls, the PCM solidifies, releasing its stored latent heat. A large number of PCMs are available in the temperature range of -5 to 190°C [12,15]. Within the human comfort range of 20 – 30°C , some PCMs are very effective [15]. They store 5–14 times more heat per unit volume than conventional storage materials such as water, masonry, or rock. The most commonly used PCMs are salt hydrates, fatty acids, esters and various paraffins (such as octadecane). Recently, ionic liquids were investigated as PCMs. The temperature range offered by PCM technology provides new possibilities for building services and refrigeration engineers, regarding medium- and high-temperature energy storage applications. This thermo-energy is widely used for cooling and heating and for thermal energy storage applications.

This review of the literature shows that phase change materials and thermoelectric materials are good candidates for, respectively,

the storage and harvesting of energy. To our knowledge, few studies [20] have aimed to link thermoelectric and phase change material effects in the harvesting of ambient energy. The purpose of this study is precisely to combine thermoelectric and latent heat effects to harvest micro-energy in low ambient heating. The aims of the article are:

- (i) To analyze a method of changing an ambient time variation of temperature loading to a space variation of temperature on a thermoelectric generator.
- (ii) To propose a solar micro-energy harvesting system (TEG & PCM unit) based on the thermoelectric effect accompanied by latent heat.
- (iii) To present a numerical method and a specific loop program to analyze the proposed (TEG & PCM) unit for the harvesting of micro-energy in ambient loading (sun radiation during day and thermal convection during night).
- (iv) To theoretically evaluate the harvested micro-energy based on the proposed (TEG & PCM) work unit.

In the next section, we present the principle of the thermoelectric effect coupled with latent heat. Section 3 deals with the design and modeling of a prototype energy harvesting work unit. In Section 4, we estimate the harvested micro-energy, based on the proposed unit, the actually recorded daily temperature and the experimental values of material properties in the unit.

2. Principle of the thermoelectric effect coupled with latent heat

As mentioned in Section 1, many experimental energy harvesting systems have been described in scientific papers. They are based on commercial thermoelectric modules, and almost all of them are based on the hypothesis that the TEG element works with a constant temperature difference between its two faces. In practice, the thermoelectric energy harvesting system based on thermal loading from solar radiation is very different. The loading on the TEG is a time-variable temperature difference. The main change of temperature difference during a day is due to the time-varying angle of incidence of sunlight on the hot face of a TEG. In order to maintain a relatively low temperature on the cold face of the TEG, it is always connected to a metallic heat sink exposed to the air.

There are two problems with this widely used system:

- The temperature on the cold face of the TEG rises rapidly when the air around the heat sink is heated by solar radiation and the convection between them decreases.
- The system can only work during the day, when solar radiation acts directly as the heat source.

In this paper, we propose the use of phase change material to accompany the working process of the TEG, improving the temperature stability on its face and extending the work time of the entire system into the night. The basic proposal is shown in Fig. 1. The phase change material (PCM) is placed at the back of the TEG where it is not irradiated by the sun. The PCM is placed in an insulating material in order to apply no heat exchange with the external environment except through the contact face with the TEG.

So, when the hot face of the TEG is loaded by solar radiation (see Fig. 1a), the heat flow passes through the thickness of the TEG and is conducted to the PCM which, initially, is in a solid state. As the absorbed heat in the PCM increases, the temperature rises until it reaches its melting point. If we choose a PCM with sufficient latent heat, a suitable fusion temperature and sufficient volume, the temperature on the cold face of the TEG remains relatively stable over

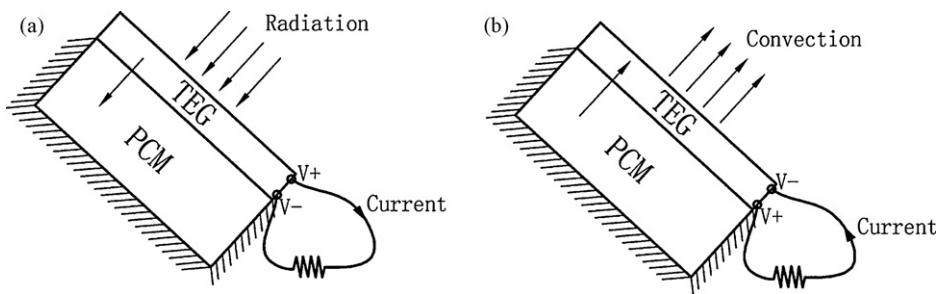


Fig. 1. Sketch map of the energy harvesting idea: (a) solar radiation on the TEG element during the day and (b) PCM work as the heat source at night.

Table 1
Properties of materials used in the work unit.

Material properties	TEG	PCM	Aluminum
Density (kg/m ³)	3790	900	2700
Conductivity (W/(m·°C))	0.5	0.18	237
Specific heat (J/(kg·°C))	840	2500	880

the whole day, as the PCM's temperature does not change enormously when it becomes liquid. We consider that the PCM changes completely into a liquid state after an entire day's heat.

At night, the hot face of the TEG loses its high temperature thermal loading and becomes the cold face (Fig. 1b). Meanwhile, the cold face of the TEG during the day, connected to the PCM, still maintains the temperature at around the melting point of the PCM. It can be higher than the temperature on the face that is connected to the external environment during the night. At this time, therefore, the PCM works as the heat source and the heat flows from PCM to TEG. Again, the TEG can harvest energy during this period. We could also choose appropriate PCM parameters to let it freeze completely during the night. We would expect this system to work non-stop, day and night. If we connect a resistor directly to the TEG, the output current could be reversed at the change between day and night.

3. Design and modeling of a prototype energy harvesting work unit

3.1. Determination of the thermoelectric device and phase change material

We chose a TEG and a typical PCM for determining the basic material properties of the system. A commercial TEG module (universal model TEC1-12708, provided by Huawei Cooling Device Co. Ltd.) and a PCM (provided by DuPont™ Energain™) are used in our system. Their basic parameters are listed in Table 1. The TEG module is 40 mm in length and width, and is 3.2 mm thick. Pre-testing showed that the Seebeck coefficient of TEG module TEC1-12708 at room temperature (15 °C) is about 30 mV/°C and the internal resistor is about 2 Ω at the same temperature.

The thermodynamic model of the TEG module is complex. The conductivity of the TEG in Table 1 is an equivalent value calculated from previous research [21] by Jia et al. It enables us to neglect the internal heat transfer between thermoelectric elements and to consider the TEG as a thermal isotropic material. The density of the TEG module is also an equivalent mean value, calculated from its weight and volume. The specific heat comes from the ceramic layer of the TEG module which is made from Al₂O₃ material.

The PCM is made of a copolymer and paraffin wax compound. In this thermal mass material, the wax melts and solidifies at around 22 °C and 18 °C respectively. As the compound melts, heat is absorbed from the room and, when it re-solidifies, it releases heat back into the room. In order to model a PCM in ANSYS, we defined

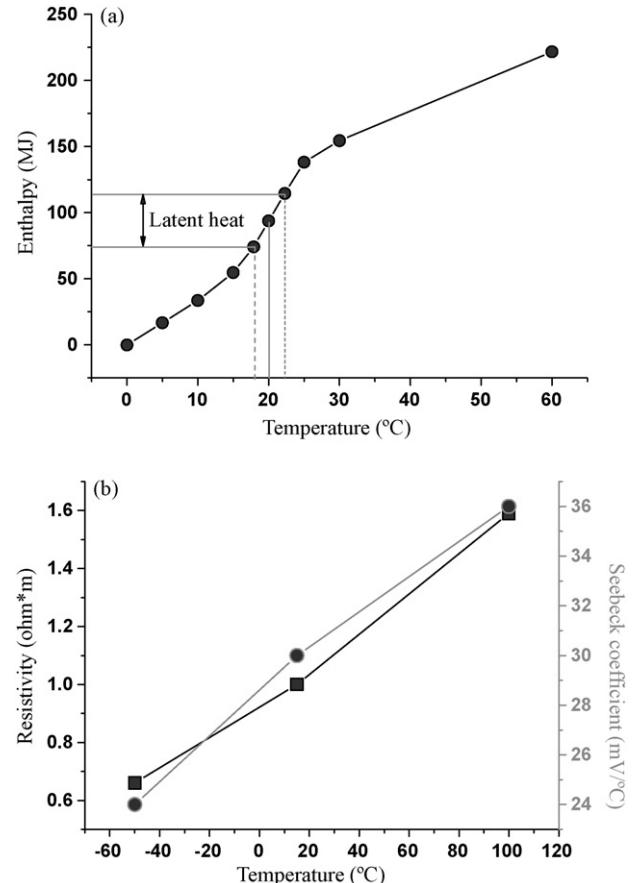


Fig. 2. Temperature dependent material properties of (a) the PCM and (b) the TEG.

an enthalpy curve to describe its heat storage capacity. Using a prior experimental test of its specific heat as a function of time, we drew the enthalpy curve below (Fig. 2a). It is obvious that the melting point is around 20 °C. When transforming, the PCM is allowed to change its temperature from 18 °C to 22 °C, at which point the latent heat available between these temperatures is around 40 MJ/m³.

3.2. Construction of the system structure

The conductivity of the PCM is relatively small, as shown in Table 1. It implies poor heat absorption or release on the contact face when working. An extra structure should be used to improve the internal thermal conductivity of the PCM, particularly so that the parts far from the contact face work effectively. Previous studies [22–24] have proved that a fork-shaped structure could strengthen the internal heat transfer in PCM, so a typical fork originally designed for cooling a CPU was adopted in the work unit, as shown in Fig. 3a. There are 35 fingers in total, each measuring

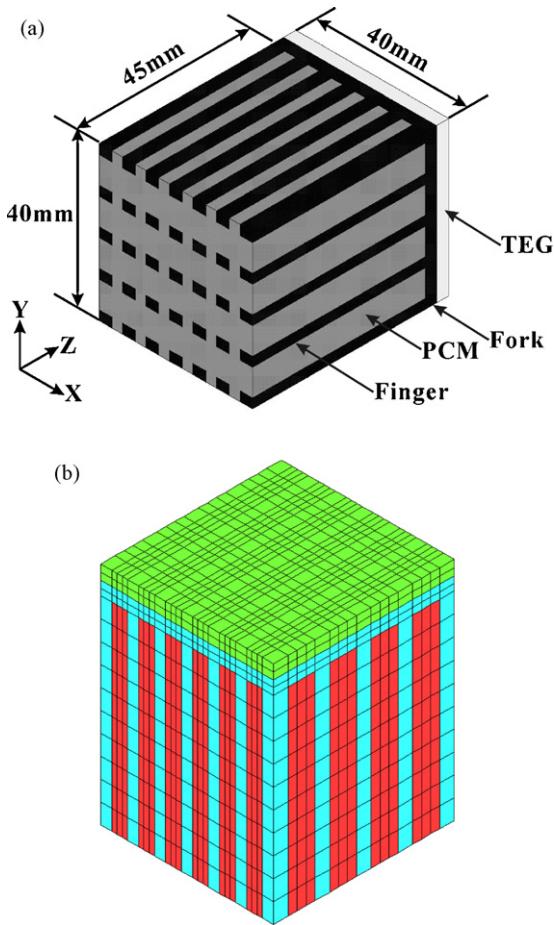


Fig. 3. Geometric prototype: (a) work unit (TEG & PCM) and (b) meshed model.

3.3 mm × 2.5 mm × 45 mm. The connecting part of the fork is 3 mm thick.

3.3. Modeling of the energy harvesting process by work unit

3.3.1. Basic assumptions in the numerical modeling process

ANSYS software is used to inspect the voltage generated by the TEG module when it undergoes time-varied loading. Five basic assumptions are proposed in the calculations:

- (1) The PCM is always considered as a solid material in the numerical models. The internal heat is only transferred by conduction. The PCM is suitable for such treatment since an ordinary ambient thermal load cannot produce a sufficiently high internal temperature or a temperature gradient able to yield strong convection in the liquid PCM.
- (2) The commercial thermoelectric device is considered as a thermal isotropic volume with dimensions of 40 mm × 40 mm × 3.2 mm. The internal sub-structure of this device is neglected.
- (3) The Seebeck coefficient $\alpha(T)$ and electrical resistance $R_{in}(T)$ of the thermoelectric material is associated with temperature, as shown in Fig. 2b. Previous literature [22] which reveals a typical relationship between these parameters and temperature is cited in our study.
- (4) P&F (the PCM and the fork structure) have no heat exchange with the external environment except for the contact face with the TEG. This could be achieved by placing insulating material around the side and bottom surfaces of the work unit.

- (5) The TEG is loaded with equivalent heat on the contact face with environment. There are three basic ambient parameters which influence the heat exchange on this face – the intensity of solar radiation, the ambient temperature and the wind speed which induces force convection. We will subsequently show the implementation of these loads in the ANSYS program, using a specially developed method.

3.3.2. Computation model of the work unit

The dimensions of the work unit are input to ANSYS according to the actual situation, and the temperature dependent material properties are defined as table information. The PCM and the fork are meshed with element solid90 while the TEG is meshed with element solid226. The element solid90 has 20 nodes with temperature as the single degree of freedom at each node. It is applicable to a 3D, steady-state or transient thermal analysis. The element solid226 also possesses 20 nodes but with up to five degrees of freedom per node. The field key of this element is activated as 110, enabling a thermal-electric analysis. It guarantees that both temperature and voltage are chosen as degrees of freedom while the corresponding force labels are heat flow and electric current. An established numerical model is shown in Fig. 3b. There are a total of 5950 elements in the meshed model.

A constant 2Ω external resistor R_{ext} , which equals to the internal resistor $R_{in}(T)$ at room temperature (15°C), is connected to the two faces of the TEG in the Z-direction. It is an optimized choice of impedance matching which can achieve maximum output energy. According to constitutive equations of thermoelectricity, the current generation is determined below:

$$I = \frac{\alpha(T) \times (T_h - T_c)}{R_{ext} + R_{in}(T)} = \frac{\alpha(T) \times \Delta T}{R_{ext} + R_{in}(T)} \quad (1)$$

It clarifies the variation in output performance which is brought by the temperature dependent material properties $\alpha(T)$ and $R_{in}(T)$. The total temperature gradient across the thickness direction of the TEG ΔT is proportional to the current generation and it represents the Seebeck effect.

3.3.3. Implementation of the ambient thermal loading

Typical records for intensity of solar radiation, daily temperature variation and wind speed (from 6:00 am on 09/07/1998 to 10:00 pm on 11/07/1998), as provided by LOCIE Polytech Savoie, are shown in Fig. 4 with a black curve. The modeling of these entire ambient thermal loads in ANSYS is implemented in the following steps:

- (1) When the outer face of the TEG is irradiated by solar radiation, the heat input rate is considered to have a simple linear relationship with the intensity of radiation which mainly depends on the gray scale of the ceramic layer. It is assumed that 50% of the radiation is used by the TEG which is equal to the input heat flux (h_{in}) as indicated by the gray curve in Fig. 4a.
- (2) The ambient temperature acts on the TEG indirectly by convection throughout the day.
- (3) Forced convection is associated with wind speed according to established theory [25]. The transformation is clarified below by an experimental formula:

$$h_w (\text{W m}^{-2} \text{K}^{-1}) = 5.678 \left\{ a + b \left[\frac{(294.26 / (273.16 + T_{ext})) V_w}{0.3048} \right]^n \right\},$$

$$V_w < 4.88 \text{ m/s} : \quad a = 0.99, \quad b = 0.21, \quad n = 1$$

$$4.88 \leq V_w \leq 30.48 \text{ m/s} : \quad a = 0, \quad b = 0.5, \quad n = 0.78 \quad (2)$$

where h_w is the convection coefficient, V_w is the wind speed and T_{ext} is the ambient temperature. a , b and n are empirical constants

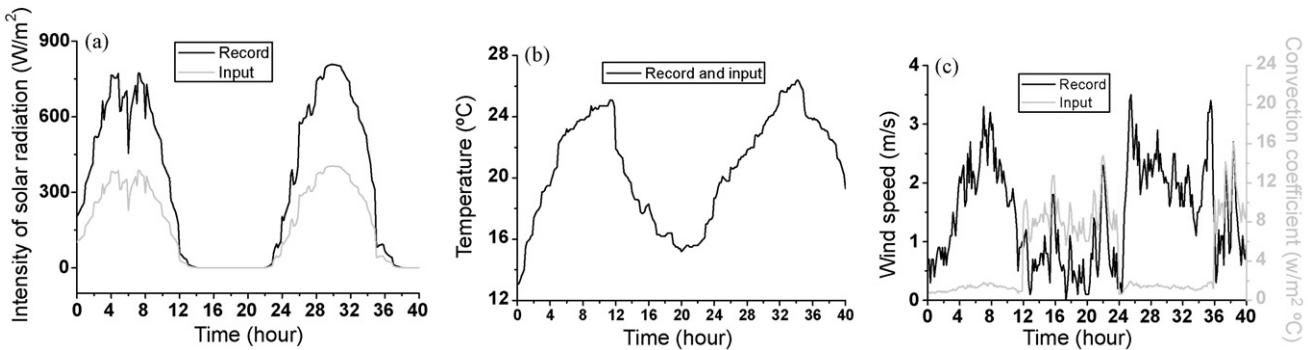


Fig. 4. A typical ambient thermal loading: (a) intensity of solar radiation (b) ambient temperature and (c) wind speed (forced convection generation).

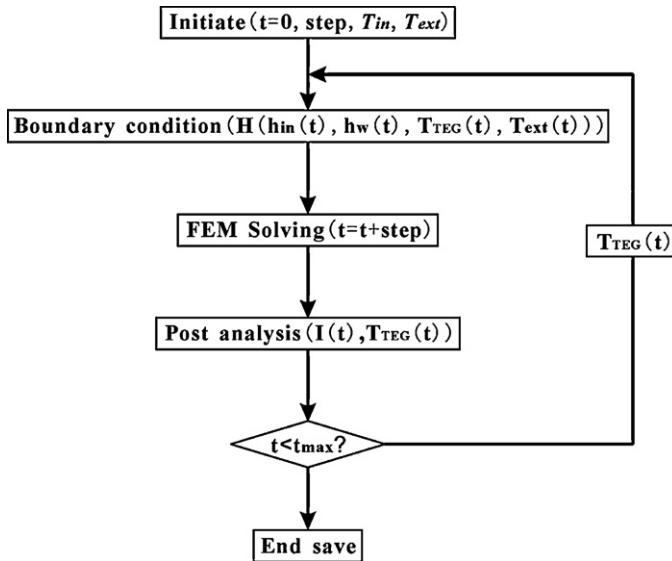


Fig. 5. Diagram for the calculation process in ANSYS simulation.

which depend on the Nusselt–Jürges correlation. It is obvious that we need weak convection on the TEG during the day and strong convection at night. We assumed that some extra technique could reduce the strength of the forced convection by 10 times during the day (from 6:00 am to 6:00 pm each day), in which case the total calculated convection coefficient is achieved as shown by the gray curve in Fig. 4c.

The combination of these ambient loads as an equivalent heat flux is illustrated below:

$$H(W \cdot m^{-2}) = h_{in} - h_w \times (T_{TEG} - T_{ext}) \quad (3)$$

T_{TEG} is the real-time temperature on the outer face of the TEG; it can be refreshed by each short period of calculation and used as a loading condition for the computation at the next step. Fig. 5 shows the implementation process for the simulation in ANSYS. In the first part, a special time step for calculation, influencing the accuracy of the simulation, needs to be defined. It can be determined by the sampling rate (1 record per 10 min) of the ambient loading adopted.

3.3.4. Determination of a suitable time for simulation

The daily atmospheric temperature variation (in spring and autumn) can be described, generally and approximately, by the formula below (unit of time: second):

$$T(t)(^{\circ}C) = 20 + 10 \times \sin \left(\frac{2\pi}{60 \times 60 \times 24} t \right) \quad (4)$$

The temperature fluctuates between 10 °C and 30 °C. The melting point of the selected PCM is in accordance with the average temperature, enabling the maximum utilization of latent heat. We can estimate the volume of PCM that is sufficient for heat storage in daytime from Fourier's law:

$$\begin{aligned} V_{PCM} &= \frac{K_{TEG} \times A_{TEG} \times dT \times \Delta t}{t_{TEG} \times \Delta G} \\ &= \frac{0.5 \times (0.04 \times 0.04) \times 10 \times (60 \times 60 \times 12)}{0.0032 \times (40 \times 10^6)} \\ &= 2.7 \times 10^{-3} m^3 \end{aligned} \quad (5)$$

where K_{TEG} , A_{TEG} , t_{TEG} signify, respectively, conductivity, area in the XY plane and thickness in the Z-direction of the TEG module. dT represents the average temperature difference on the TEG in daytime and we use the half-amplitude of input temperature loading to substitute this value, so the calculated volume should be larger than the necessary volume. Δt represents the time of half a day and ΔG represents the latent heat per unit volume as mentioned in the first step. The volume of the PCM in our prototype work unit is $7.2 \times 10^{-5} m^3$ – 37 times smaller than the calculated necessary volume. The duration of an actual ambient thermal loading in simulation could thus be reduced by 37 times in order to compensate for this mismatch.

4. Simulation results and discussion

When all the preparation is completed, the simulation is initiated and the continuous 40 h ambient loading is decreased to 5000 s in the program. Some important performance characteristics are predicted by the numerical modeling method:

- (1) The generated electric current in the external resistor is shown by black curve in Fig. 6a. The daily current (from 0 h to 12 h) is positive and the night current (from 12 h to 24 h) is negative. It proves the feasibility illustrated in Section 2.
- (2) It is obvious that the current generated during the day is similar to the intensity of input solar radiation. This indicates a potential simple linear relationship between them. The night part contains a partial negative peak value which is in agreement with the maximum local convection coefficient. It proves that the conditions are favorable for energy harvesting at night.
- (3) The maximum current passing through the external resistor reaches 15 mA during the day and the total harvested energy $E(t)$ as a function of time is shown by red curve in Fig. 6a. It is achieved simply by the formula below:

$$E(t) = \int_0^t I(t)^2 \times R_{ext} dt \quad (6)$$

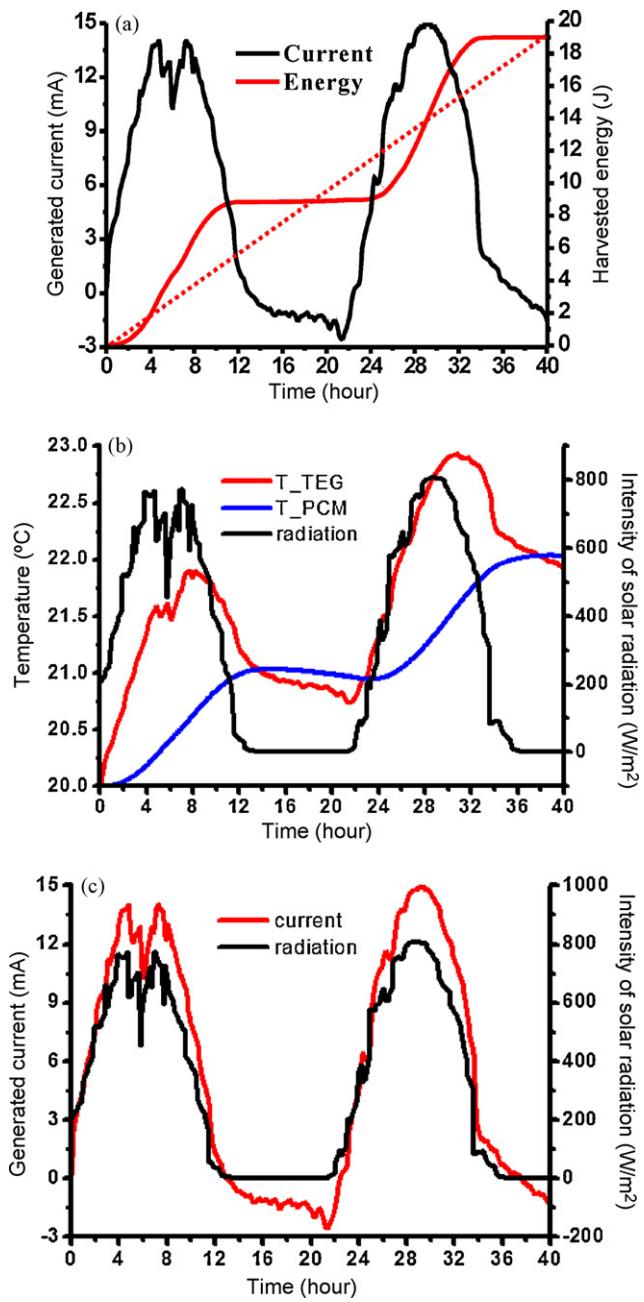


Fig. 6. (a) Current generation and the harvested energy in the external resistor. (b) Temperature variation in the TEG and PCM with corresponding solar radiation. (c) Current generation with corresponding solar radiation.

where $I(t)$ stands for the instantaneous current calculated. The total harvested energy during 40 h reaches 19.1 J which equals to an average output power around $133 \mu\text{W}$, as indicated by the slope of the red dashed line in Fig. 6a. This power is generated from a maximum intensity of solar radiation of 800 W m^{-2} and a minimum ambient temperature of 13°C . It can be improved by the heat absorption rate on the surface receiving the radiation. (4) The temperature variation in the middle part of the TEG and the PCM are shown by red and blue curve in Fig. 6b respectively. The trend of increasing temperature in the PCM reveals an accumulation of heat internally. It indicates that insufficient heat is released from the PCM to the environment at night. Further techniques, such as putting a heat sink on the surface of the TEG to enhance the forced convection, are needed to optimize system performance.

5. Conclusion

The use of a TEG to harvest ambient thermal loading and of a PCM as heat storage to prolong the work time of the TEG is investigated in this paper. The prototype work unit was constructed according to the basic rule of maximizing the temperature gradient on the thermoelectric transducer. In order to simulate a real situation, material properties are associated with temperature in the numerical model while all kinds of typical ambient loading are implemented in the simulation process by a specially developed diagram in ANSYS. The numerical analysis predicts the generation of quasi-static current in the resistor with a one-day alternating period. It is also very convenient to use this method to take account of other kinds of influence – such as a variation of harvested energy due to the reduction of convection.

The simulation reveals that the total performance of such a system is significantly dependent on the intensity of solar radiation and the thermal characteristics of the system. The trend of the generated current by TEG during the day is quite proportional to the variation of the intensity of solar radiation as shown in Fig. 6c. It can generate 2 mA current in the TEG for each 100 W m^{-2} input intensity of solar radiation.

The optimization of the system's thermal structure can be done in three ways. First, the enhancement of the heat absorption rate on the irradiated surface could be achieved by increasing its gray scale. Second, techniques which thermally isolate the solar collecting surface from the environment during the day or enlarge the contact surface between the TEG and the environment at night are both favorable in the newly developed energy harvesting system. Third, increasing the latent heat of the PCM by selecting another material is also suitable.

Further efforts could be made to verify the actual performance of such a work unit with time-variable thermal loadings which will be addressed in our upcoming experimental analysis.

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